Final Technical Report for NASA Grant NAG 5–8055

"A Global Magnetohydrodynamic Model of Jovian Magnetosphere"

The goal of this project was to develop a new global magnetohydrodynamic model of the interaction of the Jovian magnetosphere with the solar wind. Observations from 28 orbits of Jupiter by Galileo along with those from previous spacecraft at Jupiter, Pioneer 10 and 11, Voyager 1 and 2 and Ulysses, have revealed that the Jovian magnetosphere is a vast, complicated system. The Jovian aurora also has been monitored for several years. Like auroral observations at Earth, these measurements provide us with a global picture of magnetospheric dynamics. Despite this wide range of observations, we have limited quantitative understanding of the Jovian magnetosphere and how it interacts with the solar wind. For the past several years we have been working toward a quantitative understanding of the Jovian magnetosphere and its interaction with the solar wind by employing global magnetohydrodynamic simulations to model the magnetosphere. Our model has been an explicit MHD code (previously used to model the Earth's magnetosphere) to study Jupiter's magnetosphere [*Ogino et al.* 1998]. We continue to obtain important insights with this code, but it suffers from some severe limitations. In particular with this code we are limited to considering the region outside of $15R_J$, with cell sizes of about $1.5R_J$. The problem arises because of the presence of widely separated time scales throughout the magnetosphere. The numerical stability criterion for explicit MHD codes is the CFL limit and is given by $C_{\max}\,\Delta t/\Delta x < 1$ where C_{max} is the maximum group velocity in a given cell, Δx is the grid spacing and Δt is the time step. If the maximum wave velocity is C_w and the flow speed is C_f, $C_{\max} = C_w + C_f$. Near Jupiter the Alfven wave speed becomes very large (it approaches the speed of light at one Jovian radius). Operating with this time step makes the calculation essentially intractable. Therefore under this funding we have been designing a new MHD model that will be able to compute solutions in the wide parameter regime of the Jovian magnetosphere. This work was carried out in collaboration with Dr. Jon Linker at SAIC.

Several years ago we developed the Magnetohydrodynamic Algorithm for Planets (MAP) to model the interaction between Jovian plasma and the moons of Jupiter [*Kivelson et al.*, 1996a,b, *Linker et al.*, 1998, *Kivelson et al.*, 1998]. The form of the MHD equations that we solve is given by:

$$\frac{\partial \mathbf{A}}{\partial t} - \mathbf{v}\times\nabla\times\mathbf{A} = -\eta\,\nabla\times\nabla\times\mathbf{A} \tag{1}$$

$$\frac{\partial p}{\partial t} + \nabla\cdot(p\mathbf{v}) = S \tag{2}$$

$$\frac{\partial P}{\partial t}+\nabla\cdot(P\mathbf{v})=(\gamma-1)\left(-P(\nabla\cdot\mathbf{v})+\eta J^2+\frac{S(v^2+v_s{}^2)}{2}\right) \tag{3}$$

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t}+\mathbf{v}\cdot\nabla\mathbf{v}\right)=-\nabla P+\mathbf{J}\times\mathbf{B}-S(\mathbf{v}-\mathbf{v}_s) \tag{4}$$

Here $\mathbf{A}$ is the vector potential, $\mathbf{B}=\nabla\times\mathbf{A}$ is the magnetic field, $\mathbf{J}=\nabla\times\mathbf{B}$ is the current density, ρ is the plasma density, $\mathbf{v}$ is the velocity, P is the pressure, γ is the ratio of specific heats, η is the resistivity, S is the number of ionization events times the ion mass per unit volume per unit time, and v_s is the local velocity of neutrals prior to ionization. Viscous terms (necessary for capturing sharp fronts) also appear in equations (3) and (4), but we have omitted them here for simplicity. The equations are solved in spherical coordinates on a non-uniform mesh allowing grid points to be distributed more finely in regions of interest. Temporal derivatives are advanced with leapfrog time differencing combined with a semi-implicit method (described below); centered spatial differencing is used for the terms appearing on the right hand side.

In the semi-implicit approach we introduce a term into the momentum equation (4) that effectively modifies the inertia of the short-wavelength modes while accurately treating the long wavelengths, enabling the time step to exceed the CFL limit. The code takes 10 to 50 times less time to run than a comparable explicit method. When the time step is reduced below the CFL limit the method becomes identical to an explicit method.

Under funding from this grant, along with our partners at SAIC, we developed a magnetospheric version of this code. The code has successfully been used to model a magnetosphere without corotation at Jupiter's orbit. The next step in this process will be to add rotation to the simulation code. Note while the grant at UCLA has ended the companion contract at SAIC has a few months to run. This will enable us to get the rotating version working.

We plan to calibrate our new code by using our older code in the regions where the older code is valid. To that end we have used the older code to study the effects of the solar wind dynamic pressure and interplanetary magnetic field (IMF) on the configuration of the Jovian magnetosphere [*Walker et al.*, 2001]. We found that both the solar wind dynamic pressure and the IMF can cause substantial changes in the magnetosphere. On the dayside when the pressure increases the bow shock and magnetopause move toward Jupiter and the equatorial magnetic field in the middle magnetosphere becomes more dipole-like. When the pressure decreases the boundaries move farther from Jupiter and the dayside magnetic field becomes stretched out into a more tail-like configuration. For northward IMF the boundaries move toward Jupiter but the field becomes more tail-like while for southward IMF the boundaries move away and the field becomes more dipole-like. These changes are qualitatively consistent with those observed on spacecraft passing through the dayside magnetosphere. However, we were not always able to get quantitative agreement. In particular the model does not reproduce the extremely tail-like

magnetic field observed during the Pioneer 10 and Ulysses inbound passes. Tailward flows were found in the nightside equatorial plasma sheet for most IMF orientations. Both inertial effects and the IMF influence reconnection in the tail. The only time the tailward flow in the magnetotail stopped was during prolonged intervals with southward IMF. Then reconnection in the polar cusp caused the flow to move out of the equatorial plane.

We also began using the Jupiter simulations to interpret auroral observations [*Waite et al.,* 2001]. On Septerber 22, 1999 the Hubble Space Telescope observed a rapidly evolving, very bright and localized emission poleward of the main auroral oval. We used the simulation to model the mapping of the auroral flare along magnetic field lines from the polar ionosphere into Jupiter's magnetic equator and found it was connected to Jupiter's outer magnetosphere.

Papers and Presentations

Papers in Refereed Journals

1. Walker, R. J., T. Ogino, and M. G. Kivelson, Magnetohydrodynamic simulations of the effects of the solar wind on the Jovian magnetosphere, *Planet. Space Sci., 49*, 237, 2001.
2. Waite, J. H., Jr., G. R. Gladstone, W. S. Lewis, R. Goldstein, D. J. McComas, P. Riley, R. J. Walker, P. Robertson, S. Desai, J. T. Clarke, and D. T. Young, An Auroral Flare at Jupiter, *Nature, 410,* 787, 2001.

Presentations at Scientific Meetings

1. Walker, R. J., and T. Ogino, The effects of solar wind and IMF changes on the middle and outer Jovian magnetosphere, *Geophysical Research Abstracts, 1,*3, 743, 1999. Presented at the EGS Meeting, The Hague, April 1999.
2. Walker, R. J., T. Ogino and M. G. Kivelson, The influence of the solar wind and interplanetary magnetic field on the middle and outer Jovian magnetosphere, *EOS Trans. AGU, 80, S310,* 1999. Presented at the Spring AGU Meeting, Boston, June 1999.
3. Walker, R. J., Magnetic reconnection in the Jovian magnetosphere, *IUGG Abstracts,* A.377, 1999. Presented at the IUGG XXII General Assembly, Birmingham, UK, July 1999.
4. Walker, R. J., Magnetohydrodynamic simulation of the magnetospheres of the outer planets, *Magnetospheres of the Outer Planets,* p. 5, 1999. Presented at the Magnetospheres of the Outer Planets, Paris, France, August 1999.
5. Walker, R. J., T. Ogino, and M. Makino, Field aligned currents in the Jovian magnetosphere, *EOS Trans. AGU, 80,* F876, 1999. Presented at the Fall AGU Meeting, San Francisco, December 1999.
6. Walker, R. J., T. Ogino, K. K. Khurana, M. G. Kivelson and T. A. King, Currents in the Jovian magnetosphere, *EOS Trans. AGU, 81,*F1017, 2000. Presented at the Fall AGU Meeting, San Francisco, December 2000.

7. Joy, S. P., M. G. Kivelson, R. J. Walker, K. K. Khurana, and C. T. Russell, First observations from the dusk side of Jupiter near the equator: New constraints for the magnetopause and bow shock locations, *Trans. AGU, 81,* S321, 2000. Presented at the Spring AGU Meeting, Washington, D. C. May 2000.
8. Joy, S. P., R. J. Walker, M. G. Kivelson, K. K. Khurana, and C. T. Russell, A model of the Jovian magnetopause derived from spacecraft observations and MHD simulation results, *EOS Trans. AGU, 81,* F1017, 2000. Presented at the Fall AGU Meeting, San Francisco, December 2000.

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5. Ogino, T., R. J. Walker, and M. G. Kivelson, *J. Geophys. Res.,103,* 225, 1998.
6. Walker, R. J., T. Ogino, and M. G. Kivelson, *Planet. Space, Sci., 49,* 237, 2001.
7. Waite, J. H., Jr., G. R. Gladstone, W. S. Lewis, R. Goldstein, D. J. McComas, P. Riley, R. J. Walker, P. Robertson, S. Desai, J. T. Clarke, and D. T. Young, *Nature, 410,* 787, 2001.